Experimental results for Titan aerobot thermo-mechanical subsystem development

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Abstract

This paper describes experimental results from a development program focused in maturing Titan aerobot technology in the areas of mechanical and thermal subsystems. Results from four key activities are described: first, a cryogenic balloon materials development program involving coupon and cylinder tests and culminating in the fabrication and testing of an inflated 4.6 m long prototype blimp at 93 K; second, a combined lab experiment and numerical simulation effort to assess potential problems resulting from radioisotope thermal generator waste heat generation near an inflated blimp; third, an aerial deployment and inflation development program consisting of laboratory and helicopter drop tests on a near full scale (11 m long) prototype blimp; and fourth, a proof of concept experiment demonstrating the viability of using a mechanically steerable high gain antenna on a floating blimp to perform direct to Earth telecommunications from Titan. The paper provides details on all of these successful activities and discusses their impact on the overall effort to produce mature systems technology for future Titan aerobot missions.

1. Introduction

The recent and ongoing exploration of Titan by the Cassini/Huygens spacecraft has energized mission planning and technology development activities aimed at a follow-on mission. Much of this activity has been focused on *in situ* missions that explore the organic chemistry, geology and meteorology of Titan in the surface and near-surface regions (e.g., Zimmerman et al, 2006) in accordance with the scientific priorities established by the NRC Decadal survey (NRC, 2003). A combination of factors has served to promote the strategy of using a mobile aerial vehicle as the exploration platform for such a follow-on mission:

1. Results from Cassini infrared and radar images and Huygens descent images show a geologically varied surface with a large number of different, widely dispersed features including river channels, long rectilinear structures hundreds of kilometers in length, sand-dune like features and, caldera (Lorenz, 2006; Porco et al, 2005). Only an aerial vehicle will have the required mobility to visit many such sites over the course of a mission.
2. Images during the Huygens descent confirm that the near surface region is free of clouds and will thereby permit high resolution aerial imaging from altitudes up to 10 km.
3. Data from the Huygens wind experiment indicates very low winds of less than 1-2 m/s from the surface to approximately 10 km altitude (Tomasko et al, 2005). This provides a benign environment for any kind of flying vehicle.
4. Updated mission studies (Zimmerman et al, 2006) indicate that ample mass for an aerial vehicle can be delivered to Titan in relatively short transfers (6-7 years) with existing launch vehicles (Atlas 5 class).

Many different types of aerial vehicles have been proposed for Titan over the years, including balloons of various kinds, self-propelled blimps, aircraft and helicopters (Friedlander, 1984, Lorenz & Nock, 1996, Jones et al, 2000; Lorenz, 2000; Hall et al, 2002, 2004; Pankine et al, 2004). Buoyant vehicles, also known as aerobots, have emerged as the leading candidate in the majority of studies because of their ability to fly without using electrical power for lift generation, a key advantage on a highly power constrained mission. Although balloons and blimps are commonplace on Earth, adaptation for the remote, cryogenic environment of Titan requires substantial technology development in a number of key areas. Some of these areas are generally applicable to multiple kinds of Titan aerobots, like cryogenic balloon materials, while others are relevant on to one particular concept, like autonomous flight controls on a self-propelled blimp.

The work to be described in this paper consists of advances in four such key areas in aerobot mechanical and thermal components and subsystems. These are:

1. A cryogenic balloon materials development program culminating in the fabrication and testing of a 4.6 m long blimp prototype. Although a blimp shape was selected for this effort, the material and fabrication techniques are generally applicable to all types of Titan balloons.
2. A combined computational and experimental thermal analysis of the effect of radioisotope power system (RPS) waste heat on the behavior of a helium filled blimp hull. In this case, the RPS waste heat is treated as a potentially undesirable side effect on blimp buoyancy and superpressure; however, the results also contain clues for how to design hot air “Montgolfiere” type balloons for Titan.
3. Aerial deployment and inflation testing. This crucial step must be successfully executed at the start of a Titan mission without damaging the aerobot. We performed these tests on a blimp geometry, but there is significant commonality of the results to spherical and natural-shaped balloons also.
4. A proof of concept experiment with an aerobot-mounted steerable high gain antenna. All types of Titan aerobots can benefit from direct to Earth telecommunications, but significant data rates require the use of a high gain antenna that must be continuously pointed at the Earth. This successful test indicates that mechanical steering of an antenna in a representative aerobot disturbance environment can indeed achieve sufficient pointing accuracy to enable the Titan to Earth data link.

Each of these areas will now be described in detail.

2. Cryogenic Balloon Materials and Prototyping

A previous paper (Hall et al, 2004) described the baseline material we developed for a cryogenic Titan balloon. Figure 1 shows the material to be a laminate of Mylar film glued onto a polyester fabric. It was jointly developed by Lamart Inc. and JPL, with the material lamination done by Lamart. This material has an areal density of 94 g/m2, a tensile strength of 9100 N/m at 298 K, and a tensile strength of 16400 N/m at 77 K. The previous design featured a maximum blimp diameter of 3.5 m (1.75 m radius) which results in a predicted burst superpressure at 77 K of 16400/1.75 = 9371 Pa..

The new results since then consist of the successful development and demonstration of balloon fabrication with this material, in three steps:

1. Identification of and testing of glued (taped) gore-to-gore joints with both overlap and butt seams.
2. Fabrication and pressure testing of cylinders using the best adhesive and seams construction from Step 1.
3. Fabrication and cryogenic inflation testing of a 4.6 m long blimp.

A total of 6 different seams were fabricated and tested by GSSL Inc. with the baseline material consisting of both butt and overlap seams with 3 different types of adhesive tapes. The overlap seam with 38 μm (1.5 mil) Sheldahl Mylar tape was measured to have the best strength, showing 90% of the parent material strength. This was then used to construct six test cylinders.

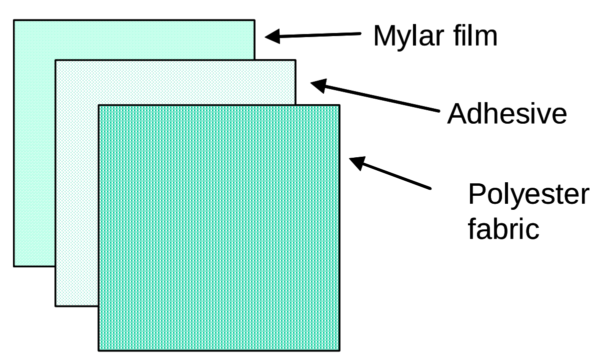

Fig. 1: Cryogenic balloon material

There were four test cylinders 10 cm in diameter and two 30 cm in diameter. These were pressure tested (Fig. 2) to failure at both 293 K and 100 K. The results are summarized in Table 1. We see no scale effect between the smaller and larger cylinders, but we do see a consistent pattern where the measured burst pressure is only 77% of the membrane stress prediction in all cases. We do not have an explanation for this result.

The final step in this prototyping process was to design, fabricate and test a 4.6 m long blimp from the baseline laminate using the overlap seam design described above. This prototype was jointly designed by JPL and GSSL, and manufactured at GSSL. It was approximately one-third the length required for a Titan aerobot mission. Although it was not designed with a tail assembly (neither elevators or rudders), it did include some structural attachment points for gondola mounting and cable tie-downs. A small but functional gondola with two electric motor driven propellers was also procured from Mobile Airships (formerly known as the Blimp Guys). This was thermally insulated and then mounted to the prototype blimp with the intention of operating the propellers during a cryogenic test as a proof of concept of the integrated system.

The finished prototype is shown in Figure 3 tied into a cryogenic test chamber at Wyle Laboratories. The blimp was inflated as shown and subjected to a Titan-like temperature of 93 K for several hours. Note that the decreasing temperature required the addition of gas to the blimp to compensate for the volumetric contraction. The flow rate into the blimp was measured throughout the experiment and no flow was detected once the 93 K temperature was reached and stabilized. This is a first order indication that the envelope was leak-free. Note that this particular test chamber featured fan-blown nitrogen gas that recirculated constantly. This subjected the prototype blimp to small but cyclical aerodynamic forces that flexed the envelope material at the tether attachment points. No cracking or other damage was observed anywhere in the envelope during post-test visual inspection. The gondola-mounted propellers functioned properly during this test while the gondola thermal insulation kept the motor temperature to a minimum of -30 ºC.

Fig. 2: Cylinder test setup

Table 1: Cylinder Test Data

Dia. (m)	Test Temp-erature (K)	Theoretical Burst Pressure (Pa)	Measured Burst Pressure (Pa)
0.1	293	182000	140000
0.3	293	60700	47000
0.1	100	328000	248000

Fig 3: Prototype blimp and gondola

3. RPS Waste Heat Analysis and Test

During conceptual design of the self-propelled blimp aerobot for Titan we were confronted with concerns about the possible detrimental effect of waste heat from the radioisotope power source (RPS) on the thermal and pressure state of the blimp. One concern is simply overpressurizing the blimp due to the heat input; another is that changing buoyancy during flight maneuvers would complicate the design of a flight control system as the changed from a free convection dominated heat transfer mode in unpropelled flight to forced convection dominated heat transfer in propelled flight. We addressed this concern with a complementary strategy: first, we performed thermal analyses of various configurations, including computational fluid dynamics (CFD) modeling of the final configuration; second, we performed a room temperature lab experiment on a full scale blimp and acquired data to compare to the model.

The design approach used was to locate the RPS below the blimp and rely on the separation distance to mix the heated plume with cold atmosphere and thereby minimize any heat transfer to the buoyancy gas. Analysis quickly showed that in forced convection mode most of the RPS heat went into the wake of the vehicle and did not affect the blimp state. Therefore, we focused the detailed CFD analysis on the case of the unpropelled blimp moving with the wind where free convection is the dominant mode of heat transport between RPS and blimp. Fig. 4 shows the geometry adopted for the CFD analysis in which a room temperature (21 ºC) scenario on Earth was used for an RPS located 1.2 m below the blimp. This first numerical study was simplified to a two-dimensional CFD analysis but with the same 2 kW of heat addition over the length of the blimp. We see that very little heating occurs of the gas inside the blimp, with an approximate temperature of only 23 ºC, just 2 ºC higher than the ambient. Modeling for a cryogenic Titan blimp showed an 8 ºC temperature rise due to RPS heating, a higher value that results from a combination of lower specific heat of the gas and reduced gas mixing in the lower gravitational field. This 8 ºC

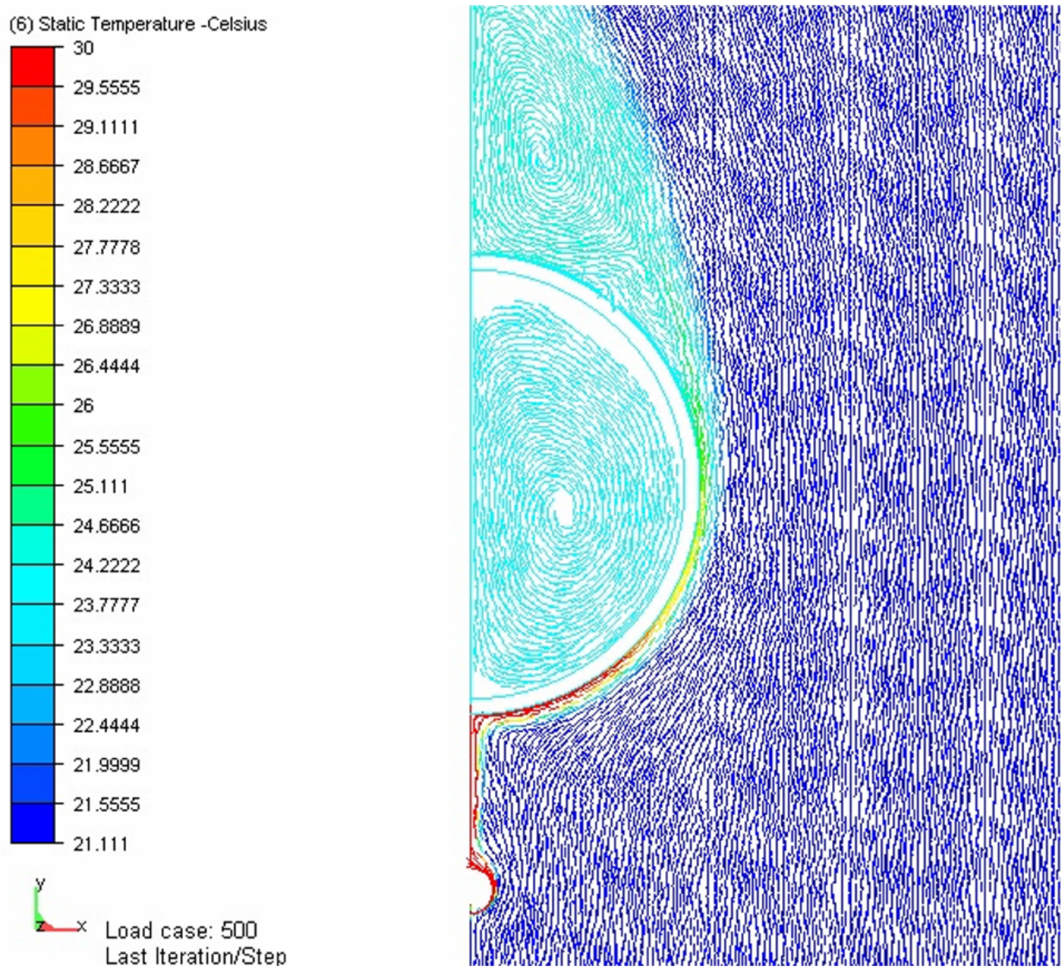

Fig. 4: 2D CFD analysis of RPS thermal effect

temperature rise at the 85 K, 100 kPa conditions of the Titan float altitude of 8 km corresponds to a rise in superpressure of 9.4 kP, which happens to be the predicted burst superpressure of the envelope as discussed in Section 2. However, this pressure rise would only occur if the blimp was being flown with completely empty ballonets; otherwise, the ballonet inflation level will automatically adjust to keep the internal pressure at its much lower nominal value of 500 Pa.

We performed a laboratory experiment to verify these CFD predictions. The test setup is shown in Fig. 5. The blimp was a conventional 11 m long ellipsoid place above a 2 kW RPS simulated heat source at a distance of 1.2 m. Thermocouples were located at multiple location inside the blimp to assess the internal heating. The laboratory used was not a carefully controlled environment, so the experiments were conducted at night with the air conditioning system turned off to produce the best temperature stability and least internal air currents.

The overall thermal results are summarized in Table 2, where the corresponding CFD values are listed for comparison. The agreement between experiment and CFD model is good and supports the conclusion that this RPS location does not pose a significant waste heat problem. Conversely, the lack of heating on the blimp gas suggests that hot-air (Montgolfiere) type balloons will require the placement of the RPS inside, and not merely close to, the balloon to effectively capture the heat for buoyancy generation purposes.

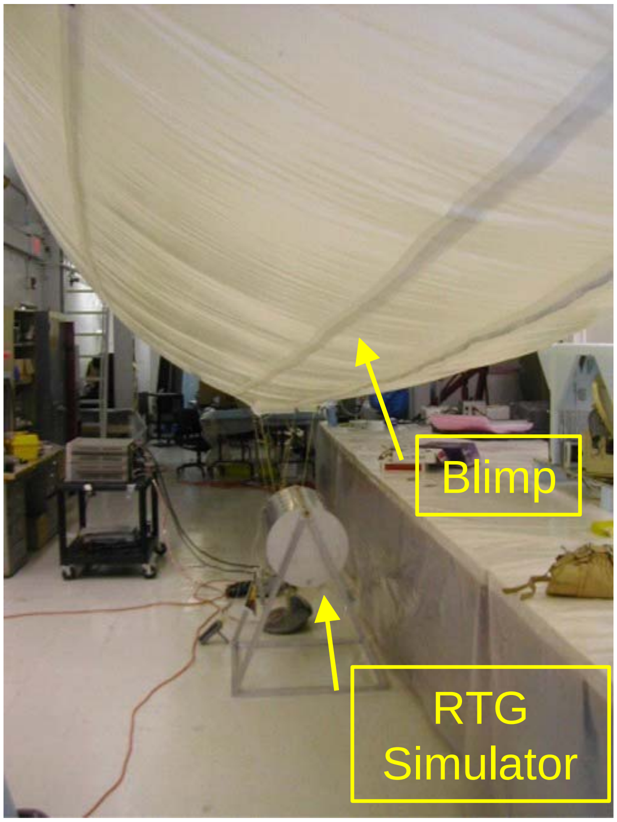

Fig. 5: RPS heating lab experiment

4. Aerial Deployment and Inflation Testing

Upon arrival at Titan, an aerobot will need to be extracted from the aeroshell, deployed into the atmosphere and filled with a buoyancy gas. If the aerobot is helium or hydrogen filled, that gas must be supplied from high pressure tanks. If the aerobot is a Montgolfiere balloon, it fills with atmospheric gas by ram air pressure, gas that then heats up using the RPS. In either case, the deployment and inflation will occur mostly under parachute descent in the lower atmosphere of Titan. The parachute is typically sized to limit the descent speed and dynamic pressure to a small value (of the order of 30 Pa) and thereby minimize the aerodynamic loading on the system. Once the inflation is complete, the parachute and gas tanks are separated and the balloon starts to fly. This was the approach used in the only planetary balloon mission to date, the two Soviet VEGA balloons that flew at Venus in 1985 (Kremnev, 1986).

The technical challenge is to prevent any damage to the aerobot during this process that involves

Table 2: RPS experiment data summary

	Expt.	CFD
Avg. ambient Temp. (ºC)	23.5	21.0
Avg. steady-state helium Temp. (ºC)	24.0	24.0
Blimp skin Temp. (avg.) (ºC)	25.0	24.5
Blimp skin Temp. (min.) (ºC)	24.0	24.0
Blimp skin Temp. (max.) (ºC)	31.0	30.0

structural loading conditions not present in the vast majority of balloon designs. Transient structural loads occur during the deployment steps, and aerodynamic loading on the partially inflated balloon tends to deform and ripple it in a manner like that of a sail on a boat or a flag in a stiff breeze. Heavy masses attached to the balloon are an additional complication because of the interface loading and the potential for abrasive contact between the component and the balloon envelope itself.

Part of the selection of the strong fabric based balloon material described in Section 2 above was motivated by the need to survive this aerial deployment and inflation process rather than the more benign float conditions. Nevertheless, it is important to engineer the system in such a way as to limit forces, prevent abrasive contact between elements and avoid tangling of with tethers or other structural elements that are used to connect the flight train together.

As a first step in this engineering process, we performed some proof of concept experiments on an 11 m long blimp. These consisted of:

1. Laboratory tests involving the deployment of the blimp from a folded condition.
2. Rapid inflation of the deployed blimp in the laboratory using a high speed air blower
3. A flight test of deployment and rapid air inflation of the blimp during parachute descent in the atmosphere.

Fig. 6 shows the blimp being inflation during the lab test. The strategy here is to keep the gondola connected to the aeroshell (or the platform in the picture that serves as a proxy) so that its weight does not pull on the blimp material during deployment and inflation. Elastic tethers are used to keep the

Fig. 6: Blimp inflation test

Fig. 7: Deployment and inflation flight test

nose and tail of the blimp tied to the parachute and hence stretched out from the gondola location to avoid drooping over the side of the aeroshell and rubbing against it in the wind. This arrangement keeps the blimp in a volume-restricted “V” shape as it fills and therefore the tethers must be cut part way through the inflation so that the blimp can stretch out to its full horizontal length and volume.

Several laboratory tests were conducted to refine the design, including the use of energy absorbing ripstitch in the tethers to mitigate shock load deployment forces and the addition of structural cross-members at the bottom of the parachute to mitigate tangling problems with the 4 tethers that otherwise would converge at a point there. The inflation test also revealed a problem with the inlet pipe design that resulted in a blimp material tear towards the end of the 5 minute inflation test. Otherwise, the rapid inflation test was successful and the inlet pipe problem was subsequently fixed.

The flight test was conducted in the Mohave desert using a helicopter to lift the flight train to an altitude of 1 km and then dropping it off to commence the parachute descent. Radio commands were sent to activate cutters and operate the air blower while the flight train fell at a speed of 5 m/s under the 11 m diameter cross parachute. Fig. 7 shows the blimp partly inflated during this flight test. Onboard video cameras showed that the blimp deployed and inflated properly during this test without suffering significant structural damage.

5. Steerable Antenna Experiment

One key problem with any kind of long duration aerobot at Titan is telecommunications with Earth. If there are no orbital assets at Titan, then direct to Earth telecom is required. Even if an orbiter is at Titan, it will be useful to have a direct to Earth link in addition for both redundancy and for telecom during those periods when the Earth is visible but not the orbiter.

Preliminary design of the direct to Earth telecom system indicates that a 1 m diameter high gain antenna can transmit approximately 1 kilobit per second of data with 15 W of radiated power to the 70 m antenna of the Deep Space Network. This is a useful data rate (corresponding to 28.8 Mbits over an 8 hour transmission period), but it requires the aerobot antenna to be pointed at the Earth within approximately 0.5 deg at all times. This tight requirement poses a significant challenge in pointing control given the continuous motion of the aerobot

Fig. 8: Detail for KVH TracVision 4 antenna

Fig. 9: Antenna mounting on blimp

due to winds, turbulence and self-propelled maneuvers.

We conducted a proof of concept experiment on one possible solution to this pointing problem, specifically that of a mechanically steered dish antenna. Our approach was to mount a commercially available antenna system on an 11 m long blimp, move the blimp in a flight-like manner and verify that it maintained a pointing accuracy on a fixed orbital target. We selected a KVH TracVision 4 system for this experiment. This 0.4 m diameter antenna is designed for satellite television reception on boats and features approximately 1 degree pointing stability for angular disturbances of up to 30 degrees per second, specifications comparable to that required for a Titan aerobot. It uses a feedback control system based on electric motor actuators in altitude and azimuth, and data from gyroscopes and the received TV signal strength.

Figures 8 and 9 show this antenna mounted under and blimp hull. This experimental setup did not include any kind of propulsion system to move the blimp; therefore, we conducted the experiment by manually moving the blimp in a "flight-like" manner using tethers connected to the nose and tail. The test results clearly demonstrated that the antenna was able to track the satellite TV signal during a variety of motions as long as the angular rates did not exceed 30 degrees per second. In fact, the inertia of the blimp was sufficient that it required "jerking" motions to generate enough of a disturbance to interfere with the signal reception. Note that the KVH TracVision 4 system is not at all optimized for this application, and it seems very likely that much better tolerance to disturbances can be engineered on any kind of properly designed system for aerobot usage.

6. Conclusions

This paper has described technical advances in four important thermo-mechanical subsystems for Titan aerobots: cryogenic balloon material, RPS waste heat effect on buoyancy gas, aerial deployment and inflation, and steerable antennas. In each case the prototyping and test results were successful and strongly indicative of technical feasibility for Titan aerobots.

7. Acknowledgements

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